

Temperature and Entropy Profiles to the Virial Radius of Abell 1246 Cluster Observed with Suzaku

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Abstract

We report properties of the intracluster medium (ICM) in Abell 1246 to the virial radius (r_{200}) and further outside as observed with Suzaku. The ICM emission is clearly detected to r_{200} , and we derive profiles of electron temperature, density, entropy, and cluster mass based on the spectral analysis. The temperature shows variation from ~ 7 keV at the central region to ~ 2.5 keV around r_{200} . The total mass in r_{500} is $(4.3 \pm 0.4) \times 10^{14} M_{\odot}$, assuming hydrostatic equilibrium. At $r > r_{500}$, the hydrostatic mass starts to decline and we, therefore, employ the total mass within r_{200} based on weak-lens mass profile obtained from a sample of lower mass clusters. This yields the gas mass fraction at r_{200} consistent with the cosmic baryon fraction, i.e. $\sim 17\%$. The entropy profile indicates a flatter slope than that of the numerical simulation, particularly in $r > r_{500}$. These tendencies are similar to those of other clusters observed with Suzaku. We detect no significant ICM emission outside of r_{200} , and 2σ upper limits of redshifted O VII and O VIII line intensities are constrained to be less than 2.9 and 5.6×10^{-7} photons $\text{cm}^{-2} \text{s}^{-1} \text{arcmin}^{-2}$, respectively. The O VII line upper limit indicates $n_{\text{H}} < 4.7 \times 10^{-5} \text{cm}^{-3} (Z/0.2 Z_{\odot})^{-1/2} (L/20 \text{ Mpc})^{-1/2}$, which corresponds to an overdensity, $\delta < 160 (Z/0.2 Z_{\odot})^{-1/2} (L/20 \text{ Mpc})^{-1/2}$.

Key words: galaxies: clusters: individual(Abell 1246) – intergalactic medium – X-rays: galaxies: clusters

1. Introduction

Clusters of galaxies, the largest virialized systems in the universe, are filled with the intracluster medium (ICM), which consists of X-ray emitting hot plasma with a typical temperature of a few times 10^7 K. X-ray spectroscopy of the ICM enables us to determine its temperature and density. Clusters are often characterized by the virial radius. Within this radius the cluster mass can be determined under the assumption of hydrostatic equilibrium (H.E.) of the ICM, and is a useful parameter for constraining cosmology. In the framework of a hierarchical structure formation based on the cold dark matter paradigm, clusters are thought to grow into larger systems through mass accretion flows which are merged into the ICM at a radius away from a few times the virial radius, along large-scale filamentary structures. The cluster outskirts around the virial radius would leave a trace of freshly shock-heated accreting matters into the hot ICM. In this sense, the outermost edge is the real front of the cluster evolution. However, because of the difficulties in observation, properties, such as temperature, density around the virial radius have not been known well yet.

Recent observational studies of clusters with Chandra and XMM-Newton, with their powerful imaging capability and large effective area, have unveiled radial profiles of

temperature, entropy, gas mass, and gravitational mass up to r_{500} within which the mean cluster mass density is 500 times the cosmic critical density and which is about a half of the virial radius (Vikhlinin et al. 2005; Piffaretti et al. 2005; Pratt et al. 2007; Vikhlinin et al. 2009; Pratt et al. 2010; Zhang et al. 2010). The derived temperature and entropy profiles to r_{500} are almost consistent with theoretical expectations from the self-similar assumption. On the other hand, the gas mass fraction $M_{\text{gas}}/M_{\text{total mass}}$ increases with radius to r_{500} , and does not exceed the cosmic baryon fraction.

Because Suzaku XIS is characterized by a lower background level especially above 3 keV and a higher sensitivity below 1 keV (Koyama et al. 2007), we have been able to observe the ICM emission beyond r_{500} region of clusters (Bautz et al. 2009; George et al. 2009; Reiprich et al. 2009; Hoshino et al. 2010; Kawaharada et al. 2010; Sato et al. 2010; Akamatsu et al. 2011; Ichikawa et al. 2013). The clusters observed with Suzaku show a similar trend; the temperature drops to $\sim 1/3$ of the peak from the center to the outskirts as expected from structure formation scenarios (Burns et al. 2010). On the other hand, the radial entropy profile has a flatter slope compared to that of numerical simulations obtained assuming adiabatic cool gas accretion (e.g. Voit 2005). In addition, Kawaharada et al. (2010) report a directional dependence of the temperature

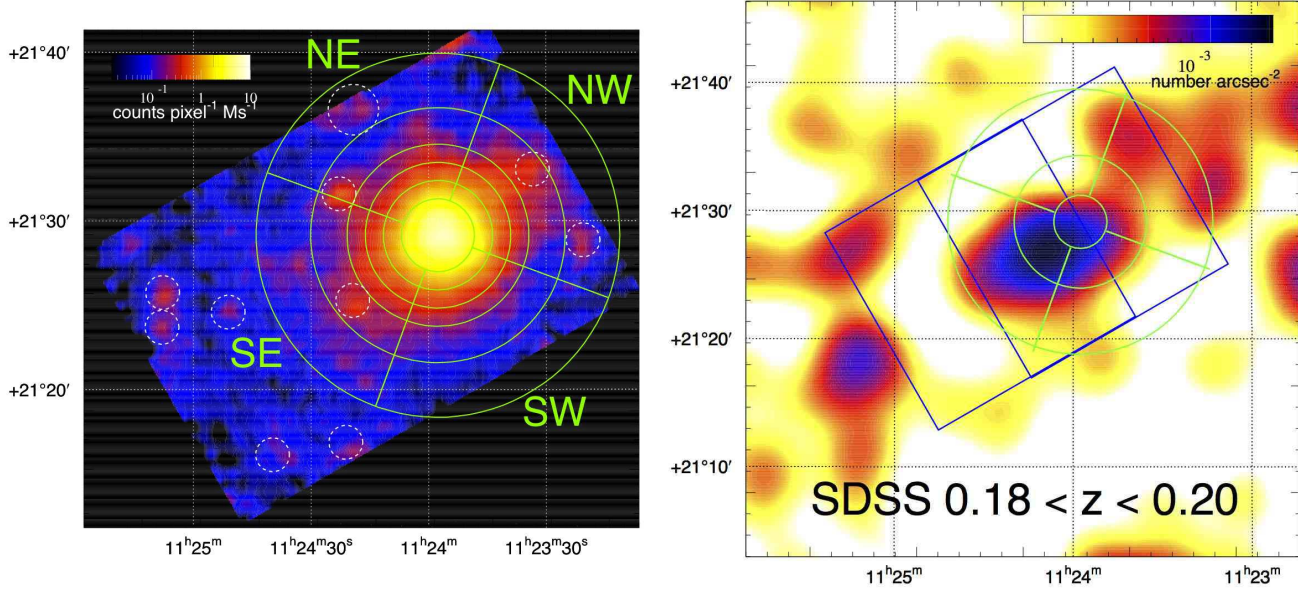


Fig. 1. Left: Combined XIS image of Abell 1246 in 0.5–5.0 keV energy range. The observed XIS0, 1, 3 images were added on the sky coordinate and smoothed with $\sigma = 16$ pixel $\simeq 17''$ Gaussian. The instrumental background (NXB) was subtracted and the exposure was corrected, although vignetting was not corrected. Green circles show the extracted regions for the spectral analysis. The subtracted point source regions are indicated by white dashed circles. Right: Galaxy number density map from the SDSS catalogue around Abell 1246. The projected galaxy number density was selected between $0.18 < z < 0.20$. The map consisting of 620 galaxies was smoothed with $\sim 2'$ Gaussian. Blue boxes show the overlapped two Suzaku observations. Green circle regions correspond to the extracted spectra regions for investigating the directional dependence of the ICM properties. For details, please see in text.

and entropy in Abell 1689 cluster which is considered to reflect the mass flow from the large scale structure filament. Thus, observing the cluster outskirts as a whole, not only the limited direction, is important.

In further outer region, as far as the virial radius, the intergalactic matter is considered to be not yet mixed with the ICM. It is the highest density component of the warm-hot inter galactic medium (WHIM, e.g., Cen & Ostriker 1999; Cen & Fang 2006), which is thought to exist along the large-scale structure as filaments. The WHIM would be also the most promising candidate for the “missing baryons”, which play key roles for investigating the inconsistency between the baryon density in the local universe and the distant universe (e.g., Fukugita et al. 1998; Rauch 1998; Takei et al. 2011). Although it is difficult to detect the WHIM with current detectors such as CCD cameras (e.g. Suzaku XIS), if observed, its thermal and chemical properties would provide rich information on the structure formation and evolution of the universe. Some challenging observations have given a constraint on the upper limit of the WHIM emission. High resolution imaging spectroscopy with Chandra and XMM-Newton is claimed to show evidences for the WHIM emission (e.g., Kaastra et al. 2003; Werner et al. 2008; Galeazzi et al. 2009). Their grating observations also make the absorption-line study and restrict the WHIM density significantly (e.g., Nicastro et al. 2005; Kaastra et al. 2006; Buote et al. 2009; Fang et al. 2010; Zappacosta et al. 2010). Recent studies with Suzaku have shown that Suzaku XIS can effectively constrain the Galactic emission

(Gupta & Galeazzi 2009; Yoshino et al. 2009) better than previous satellites. Therefore, Suzaku also has a great advantage in the WHIM search, because a reliable estimation of the foreground Galactic emission is of utmost important in constraining the WHIM emission. Although Takei et al. (2007) detect no significant redshifted O lines from the outer region of Abell 2218 with Suzaku, they set a strict constraint on the intensity (see also Tamura et al. 2008; Sato et al. 2010; Mitsuishi et al. 2012).

Abell 1246 is a cluster of galaxies characterized by a smooth distribution of the ICM. ASCA observation determined the temperature, kT and the metal abundance, Z , as 5.17 ± 0.58 keV and 0.26 ± 0.17 solar, respectively, averaged over the whole cluster (Fukazawa et al. 2004). The redshift of Abell 1246 cluster is 0.1902 from the NASA/IPAC Extragalactic Database¹. At this redshift, $1'$ corresponds to 191 kpc. Here, we use $H_0 = 70$ km s⁻¹ Mpc⁻¹, $\Omega_\Lambda = 1 - \Omega_M = 0.73$. The virial radius, r_{200} , using the mean temperature, was defined as $r_{200} = 2.77(\langle kT \rangle / 10 \text{ keV})^{1/2} / E(z)$ Mpc and $E(z) = (\Omega_M(1+z)^3 + \Omega_\Lambda)^{1/2}$ as described in Henry et al. (2009), in this paper. For Abell 1246 cluster, the virial radius, r_{200} , is 1.97 Mpc or $10.3'$ with $\langle kT \rangle = 6$ keV. Throughout this paper we adopt the Galactic hydrogen column density of $N_H = 1.57 \times 10^{20}$ cm⁻² (Dickey & Lockman 1990) in the direction of Abell 1246, and use the solar abundance table provided by Anders & Grevesse (1989). Unless noted otherwise, the errors are in the 90% confidence region for a single interesting parameter.

¹ <http://ned.ipac.caltech.edu/>

Table 1. Suzaku observation logs of Abell 1246 cluster.

Region	Seq. No.	Obs. date	(RA, Dec)* J2000	Exp. ksec	After screening (BI/FI) ksec
Abell 1246	804028010	2009-11-16T04:54:20	(11 ^h 23 ^m 59 ^s 8, +21°29′11″)	48.5	36.9/36.9
Abell 1246 offset	804029010	2009-11-28T00:30:33	(11 ^h 24 ^m 30 ^s 7, +21°25′09″)	80.4	52.1/52.1

* Average pointing direction of the XIS, written in the RA_NOM and DEC_NOM keywords of the event FITS files.

2. Observations

Suzaku carried out Abell 1246 and its offset observation in November 2009 (PI: K. Sato) to observe the outskirts of the cluster beyond the virial radius or r_{200} . The observation logs are shown in table 1, and the XIS image in the 0.5–5.0 keV energy range is shown in figure 1. The XIS was operated in the normal clocking mode (8 s exposure per frame), in the standard 5×5 or 3×3 editing mode. During these observations, a significant effect of the Solar Wind Charge exchange (SWCX) was not confirmed in ACE data ². We note that Abell 1246 observations have an attitude uncertainty, which are estimated within ~ 1 arcmin, because of a satellite house keeping system problem. We, however, conclude that the uncertainty is smaller by visual inspection, and it does not affect our results.

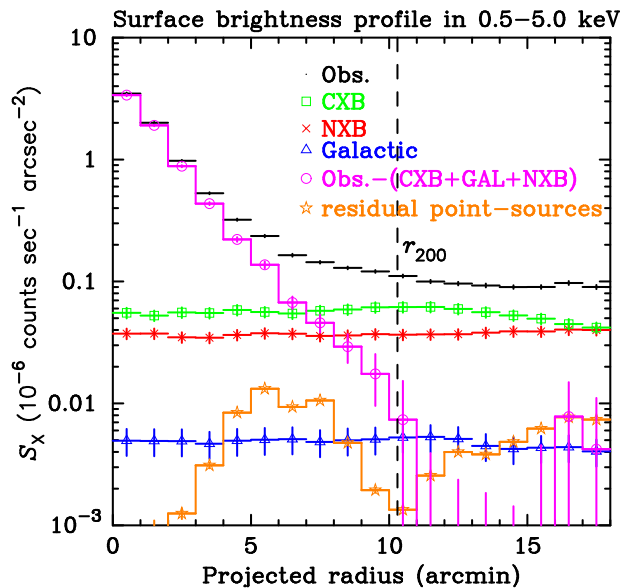


Fig. 2. Radial surface brightness profile in 0.5–5.0 keV. Point-like sources specified in figure 1 (left) are removed, but vignetting is not corrected. Observed data profile (black) is shown with the CXB (green), NXB (red), and Galactic components (blue) profiles. A resultant background-subtracted profile (black–green–red–blue) is shown in magenta. The error bars in these profiles are 1σ . In the error bars of the background-subtracted profile (magenta), the uncertainties of the backgrounds are added in quadrature to the corresponding statistical 1σ errors.

3. Data Reduction

We used version 2.4 processing Suzaku data, and the analysis was performed with HEASoft version 6.10 and XSPEC 12.6.0q. In the analysis of the XIS data, we selected ELEVATION $> 15^\circ$ of the standard data set ³ to remove stray-light from the day Earth limb. Event screening with cut-off rigidity (COR) of “COR2 > 8 ” was also performed in our data. The exposure after the screening is shown in table 1.

In order to subtract the non-X-ray background (NXB), we employed the dark Earth database using the “xisnxbgen” Ftools task. For spectral fits of the ICM emission, we generated ancillary response files (ARFs) for Abell 1246, assuming the β -model surface brightness profile as $\beta = 0.52$ and $r_c = 0.47$ (Fukazawa et al. 2004) by “xissimarngen” (Ishisaki et al. 2007). We also generated ARFs for each observation and assumed a uniform sky of $20'$ radius for the Galactic and Cosmic X-ray Background (CXB) emissions. We included the effect of the contaminations on the optical blocking filter of the XISs in the ARFs. Because the energy resolution slowly degraded after the launch due to radiation damage, this effect was included in redistribution matrix file (RMF) by “xisrmfgen” Ftools task.

4. Spectral Analysis

4.1. Subtraction of point-like sources

Using “wavdetect” tool in CIAO ⁴, we searched point-like sources in the Suzaku images in the energy range of 0.5–2.0 and 2–10 keV which were useful energy bands for detecting galaxies or galaxy groups and point-like sources, respectively. The “wavdetect” tool in CIAO is based on scalable, oscillatory functions which deviate from zero only within a limited spatial regime and have average value zero (Freeman et al. 2002). This tool, therefore, is useful for characterizing simultaneously the shape, location, and strength of astronomical sources. In addition, this algorithm operates effectively regardless of the PSF shape. Because the tool does not deconvolve the Suzaku’s PSF, we regard the sources which are detected by the algorithm and smaller than the Suzaku’s PSF as the compact diffuse or point-like sources. As shown by the white dashed circles in figure 1, we detected 10 sources as compact diffuse sources or point-like sources with the significance threshold of 3σ . The same 10 sources were also

³ http://www.astro.isas.ac.jp/suzaku/process/v2changes/criteria_xis.html

⁴ <http://cxc.harvard.edu/ciao/>

² <http://www.srl.caltech.edu/ACE/ASC/>

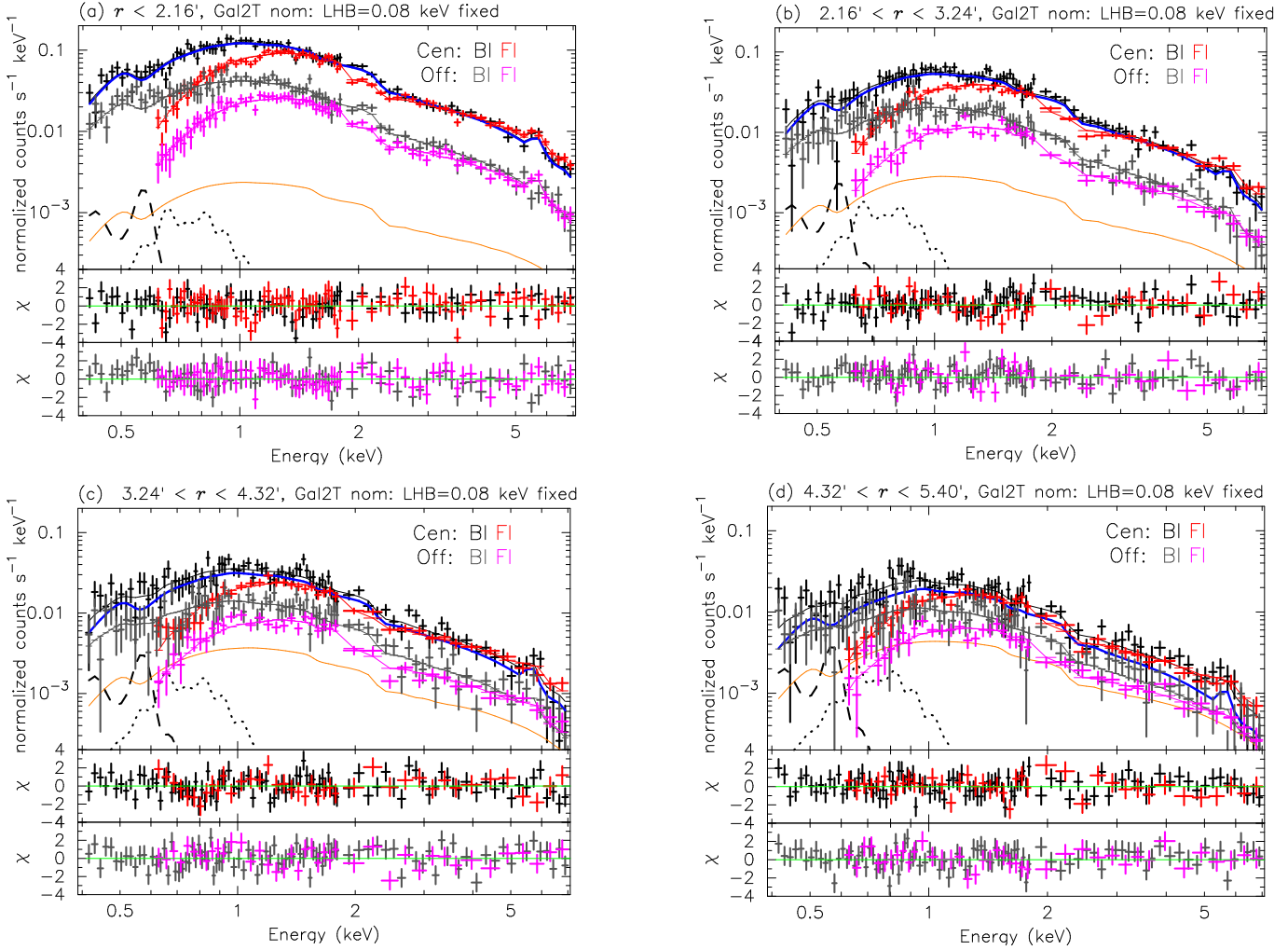


Fig. 3. The panels from (a) to (g) show the observed spectra sorted in the seven annular regions. Spectra obtained from the BI and FI CCDs of the central pointing data are presented in black and red, respectively, after subtracting only NXB. Those of the offset pointing data are in dark gray and magenta, as well. Blue lines indicate the ICM component for each annular region of (a)–(f). The LHB, MWH and CXB components for the BI spectra are shown in black-dashed, black-dotted, and orange-solid lines, respectively. The energy range around the Si K-edge (1.825–1.840 keV) is ignored in the spectral fits. The lower panels show the fit residuals in units of σ .

identified when we used another tool, “wavelet” in the SAS package⁵. We subtracted 9 point-like sources with 1 arcmin and another source with 1.5 arcmin. We checked fluxes of all the detected sources with a power-law model of the photon index to be fixed at 1.4. The flux of the faintest point-like source in 2–10 keV is $\sim 3 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$, and we estimate the CXB level and fluctuations with the value. Figure 2 shows 0.5–5.0 keV radial surface brightness profile (background inclusive, but point-like or compact sources excluded) as black crosses. As shown in Kawaharada et al. (2010), because half of the point-like source signals is expected to escape from the masked $1'$ radius region due to the PSF, we need to estimate the residual signals for the systematic uncertainties of the background as the contaminated signal. We simulated the residual signals from point sources, the Galactic and

CXB emissions using “xissim” tool (Ishisaki et al. 2007) with 10 times longer exposure time than actual observations. Here, the Galactic and CXB level were assumed to be the flux level of the default case in table 2. The estimated contaminations from the point-like or compact sources are shown in figure 2 in the orange line. In our analysis, the contributions from the residual signals and unresolved sources are included in the CXB model. In $r > 10/8$, the uncertainties of the flux are $\sim 8\%$ comparing to the estimated CXB level.

4.2. Simultaneous spectral fits for all regions

We extracted spectra from seven annular regions of $r < 2/16$, $2/16 < r < 3/24$, $3/24 < r < 4/32$, $4/32 < r < 5/40$, $5/40 < r < 7/56$, $7/56 < r < 10/8$, and $r > 10/8$, centered on ($11^{\text{h}}23^{\text{m}}57^{\text{s}}.6$, $+21^{\circ}29'09''$). The annular spectra for each observation are shown in figure 3. The spectra of both BI

⁵ <http://xmm.esa.int/sas/>

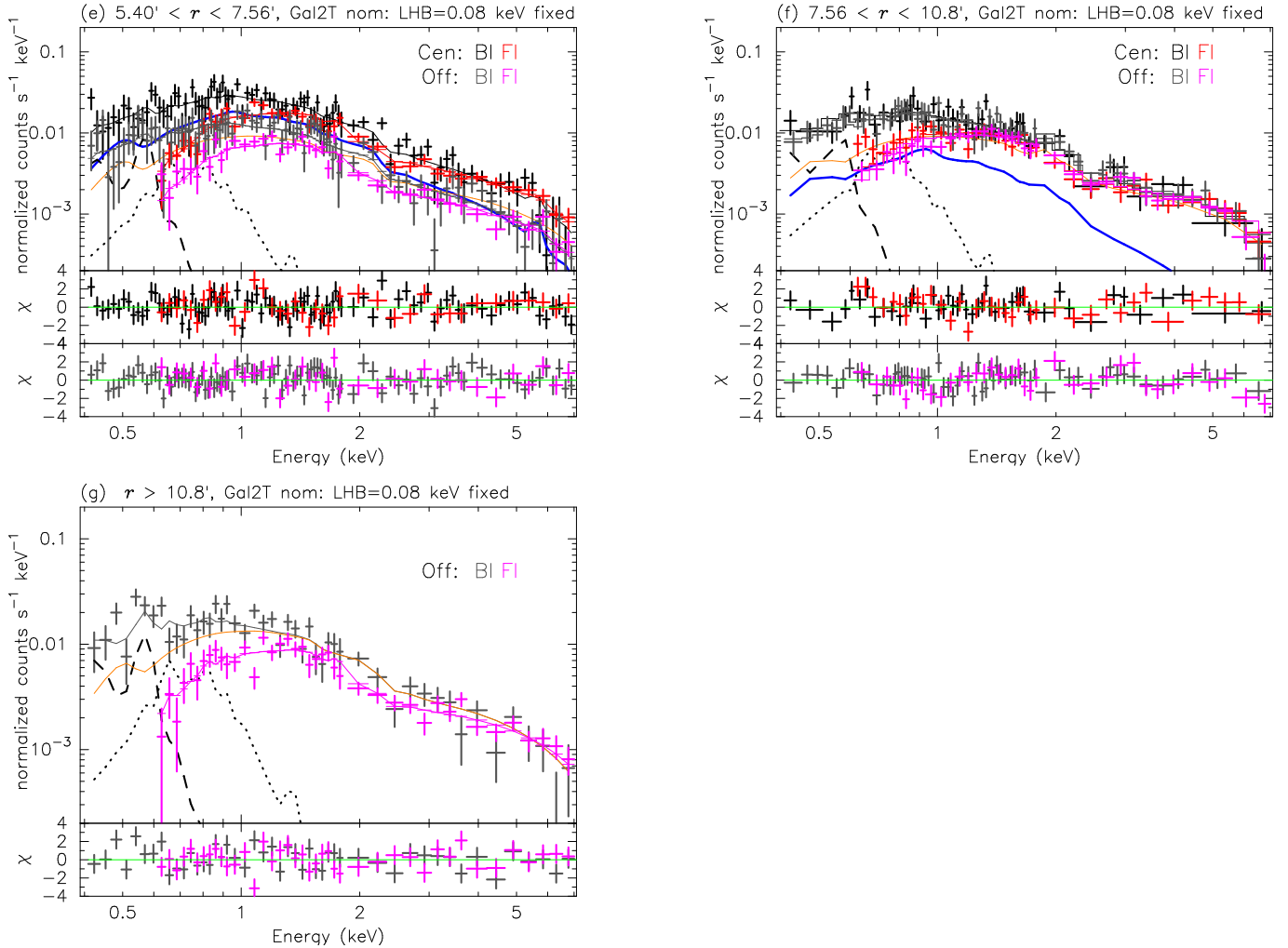


Fig. 3. continue.

and FI for all regions as shown in figure 3 (a)–(g), were fitted simultaneously in the energy range of 0.4–7.1/0.6–7.1 keV (BI/FI) for the central and offset observations. In the simultaneous fit, the common Galactic emission and CXB components were included for all the regions. We excluded the narrow energy band around the Si K-edge (1.825–1.840 keV) because its response was not modeled correctly. The energy range below 0.4 keV was also excluded because the C edge (0.284 keV) seen in the BI spectra could not be reproduced well in our data. The range above 7.1 keV was also ignored because the Ni line (~ 7.5 keV) in the background left a spurious feature after the NXB subtraction at large radii. In the simultaneous fits of the BI and FI data, only the normalization parameter was allowed to vary.

We assumed the CXB and two Galactic emissions, local hot bubble (LHB) and milky way halo (MWH) as the back- and fore- ground emissions in $r > 10.8'$ and a thermal (ICM) model for the inner region of the virial radius as follows (hereafter model I);

- model I: $\text{apec}_{\text{LHB}} + \text{phabs} \times (\text{apec}_{\text{MWH}} +$

$$\text{apec}_{r < 10.8'} + \text{pow}_{\text{CXB}})$$

Although there was no flare in the solar-wind flux during our observation, because the SWCX and LHB could be hardly distinguished with a limited spectral resolution of CCDs (e.g., Yoshino et al. 2009; Gupta & Galeazzi 2009), we modeled the sum of the SWCX and the LHB as a single unabsorbed thermal plasma. Here we assumed a zero redshift and 1 solar metallicity for the LHB and MWH emissions.

We examined the spectral fits by changing the parameters of the LHB temperature and the photon index of CXB to be either free or fixed as shown in table 2. Consequently, as shown in table 2 and 3, and figure 2 and 3, the ICM emission is significantly detected to the virial radius, and the observed spectra are well-represented by the model I in which the LHB temperature and the photon index of CXB are fixed to be 0.08 keV and 1.4, respectively.

The derived surface brightness of the CXB component in 2–10 keV is $5.88^{+0.41}_{-0.38} \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ as shown in table 2, and the estimated CXB fluctuation for the

Table 2. Summary of the parameters of the fits for model I in the $r > 10/8$ region owing to background estimation.

model I				
Const. (BI/FI)		LHB/CXB free	LHB free	default
		1(fixed)/0.97 $^{+0.05}_{-0.04}$	1(fixed)/0.98 $^{+0.08}_{-0.08}$	1(fixed)/0.97 $^{+0.08}_{-0.08}$
Galactic & CXB				
LHB	kT (keV)	0.07 $^{+0.05}_{-0.07}$	0.07 $^{+0.05}_{-0.07}$	0.08(fixed)
	$Norm^*$ ($\times 10^{-3}$)	10.39 $^{+0.25}_{-0.29}$	12.12 $^{+0.28}_{-0.28}$	6.05 $^{+1.41}_{-1.57}$
MWH	kT (keV)	0.28 $^{+0.05}_{-0.05}$	0.29 $^{+0.05}_{-0.05}$	0.29 $^{+0.06}_{-0.05}$
	$Norm^*$ ($\times 10^{-4}$)	2.45 $^{+0.74}_{-0.77}$	2.63 $^{+0.76}_{-0.73}$	2.51 $^{+0.81}_{-1.07}$
CXB	Γ	1.45 $^{+0.07}_{-0.07}$	1.4(fixed)	1.4(fixed)
	S_X^\dagger	6.13 $^{+0.55}_{-0.53}$	5.88 $^{+0.42}_{-0.39}$	5.88 $^{+0.41}_{-0.38}$
$\chi^2/\text{d.o.f.}^{\dagger\dagger}$		1965/1771	1966/1772	1966/1773

* Normalization of the *apec* component divided by the solid angle, Ω^v , assumed in the uniform-sky ARF calculation (20' radius), $Norm = \int n_e n_H dV / (4\pi (1+z)^2 D_A^2) / \Omega^v \times 10^{-14} \text{ cm}^{-5} 400\pi \text{ arcmin}^{-2}$, where D_A is the angular distance to the source.

† The 2–10 keV CXB surface brightness in units of $\times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$.

†† The χ^2 values show total values of simultaneous fits of the ICM and background components.

Table 3. Summary of the ICM parameters of the fits for model I: default.

model I: default				
Region		$r < 2/16$	$2/16 < r < 3/24$	$3/24 < r < 4/32$
Center	Const. (BI/FI)	1(fixed)/0.98 $^{+0.02}_{-0.02}$	1(fixed)/1.02 $^{+0.04}_{-0.04}$	1(fixed)/1.02 $^{+0.05}_{-0.05}$
Offset	Const. (BI/FI)	1.13 $^{+0.04}_{-0.04}$ /0.94 $^{+0.03}_{-0.03}$	1.07 $^{+0.05}_{-0.05}$ /0.94 $^{+0.05}_{-0.04}$	1.07 $^{+0.06}_{-0.06}$ /0.94 $^{+0.06}_{-0.06}$
	kT (keV)	6.80 $^{+0.41}_{-0.41}$ $^{+0.01}_{-0.01}$	6.36 $^{+0.42}_{-0.41}$ $^{+0.04}_{-0.05}$	6.17 $^{+0.60}_{-0.57}$ $^{+0.10}_{-0.11}$
	Z (solar)	0.20 $^{+0.05}_{-0.05}$ $^{+0.00}_{-0.00}$	0.18 $^{+0.09}_{-0.09}$ $^{+0.00}_{-0.00}$	0.24 $^{+0.15}_{-0.14}$ $^{+0.00}_{-0.01}$
	$Norm^*$	2.59 $^{+0.06}_{-0.06}$ $^{+0.01}_{-0.03} \times 10^{-4}$	3.40 $^{+0.12}_{-0.12}$ $^{+0.02}_{-0.02} \times 10^{-5}$	2.24 $^{+0.12}_{-0.12}$ $^{+0.03}_{-0.03} \times 10^{-5}$
Region		$4/32 < r < 5/40$	$5/40 < r < 7/56$	$7/56 < r < 10/8$
Center	Const. (BI/FI)	1(fixed)/1.02 $^{+0.07}_{-0.06}$	1(fixed)/1.02 $^{+0.08}_{-0.07}$	1(fixed)/1.04 $^{+0.11}_{-0.10}$
Offset	Const. (BI/FI)	1.07 $^{+0.08}_{-0.08}$ /0.94 $^{+0.07}_{-0.07}$	1.07 $^{+0.08}_{-0.08}$ /0.94 $^{+0.07}_{-0.06}$	1.06 $^{+0.09}_{-0.08}$ /0.91 $^{+0.08}_{-0.07}$
	kT (keV)	5.06 $^{+0.71}_{-0.56}$ $^{+0.16}_{-0.18}$	4.20 $^{+0.71}_{-0.60}$ $^{+0.32}_{-0.33}$	2.37 $^{+1.16}_{-0.90}$ $^{+0.76}_{-0.71}$
	Z (solar)	0.24 $^{+0.21}_{-0.19}$ $^{+0.00}_{-0.01}$	0.24 $^{+0.27}_{-0.24}$ $^{+0.03}_{-0.03}$	0.13 $^{+0.43}_{-0.13}$ $^{+0.00}_{-0.03}$
	$Norm^*$	1.19 $^{+0.09}_{-0.09}$ $^{+0.02}_{-0.03} \times 10^{-5}$	5.38 $^{+0.62}_{-0.62}$ $^{+0.22}_{-0.17} \times 10^{-6}$	1.60 $^{+0.55}_{-0.49}$ $^{+0.17}_{-0.05} \times 10^{-6}$

* Normalization of the *vapex* component scaled with a factor of the selected region comparing to the assumed image in “xissimarfgen”, $Norm = \text{factor} \int n_e n_H dV / [4\pi (1+z)^2 D_A^2] \times 10^{-14} \text{ cm}^{-5} \text{ arcmin}^{-2}$, where D_A is the angular distance to the source.

† The first and second errors correspond to the statistical error and the systematic errors by changing the CXB level by $\pm 10\%$, respectively.

$r > 10/8$ region is 12%. The CXB surface brightness agrees with that of Ichikawa et al. (2013), $5.17^{+0.26}_{-0.23} \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ (after subtraction of point sources brighter than $2 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$), within statistical errors taking into account the CXB fluctuation and the residual flux from the extracted point-like sources. Using the same threshold, the CXB surface brightness derived with previous Suzaku observations is $4\text{--}6 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ (e.g., Kawaharada et al. 2010; Hoshino et al. 2010), they also agree with our CXB estimation. The details of the CXB estimation are shown in Appendix 1. Because the ICM component shape around the outskirts is far from a power-law model one with a photon index of 1.4 for the CXB component, the effects from the CXB contamination would be negligible for our discussions.

We also examined whether or not an additional *apec* component (with a redshift of either zero or a cluster value) significantly improved χ^2 against a change in the degree of freedom $\delta\nu$ in the outer region of the virial radius. we assumed an additional thermal model for the outer region of the virial radius as the Galactic emission (model II) and ICM emission (model III) as follows,

- model II: $\text{apec}_{\text{LHB}} + \text{phabs} \times (\text{apec}_{\text{MWH}} + \text{apec}_{r < 10.8'} + \text{apec}_{r > 10.8'}, Z=1, z=0 + \text{pow}_{\text{CXB}})$
- model III: $\text{apec}_{\text{LHB}} + \text{phabs} \times (\text{apec}_{\text{MWH}} + \text{apec}_{\text{all regions}} + \text{pow}_{\text{CXB}})$

In case of model II, which corresponds to the zero redshift *apec* model, the improvement over the values shown in table 2 is $\chi^2 = 4$ with $\delta\nu = 2$, while the resultant tem-

perature of the additional model is $0.62^{+0.18}_{-0.16}$ keV. This is not significant in F-test. On the other hand, in the case of model III, an addition of a cluster-redshift apec model ($z = 0.1902$) results in no improvement ($\delta\chi^2 < 1$), while the temperature of the additional component is ~ 1 keV, which is comparable to the temperature reported for the WHIM emission (e.g., Werner et al. 2008).

4.3. Systematic Errors

We investigated the effect of a possible incorrect calibration, such as NXB level and contaminations on XIS optical blocking filter (OBF), by artificially changing these values by $\pm 10\%$ and comparing the resultant χ^2 value. While the temperatures of the LHB and MWH did not change within $< 1\%$ compared to the values in table 2, the normalization of the CXB model changed by $\sim 10\%$. When we examined the other uncertainty in the OBF contaminant by changing the absorber thickness by $\pm 10\%$, the temperatures of the LHB and MWH did not change within $< 1\%$, and the normalizations of the LHB, MWH, and CXB changed by $\sim 5\%$. We also changed the CXB levels by $\pm 10\%$ and $\pm 20\%$ for the fits of the azimuthal average and directional dependence, respectively, corresponding to the estimated CXB fluctuation as mentioned in Appendix 1. Even if the CXB level of the outermost region for the azimuthal average was changed by $\pm 10\%$, the resultant temperature stayed within ± 1 keV ($\sim 30\%$ change). In the case of changing the CXB level of the outer south-east region for investigating the directional dependence by $\pm 20\%$, the temperature also changed by ± 1 keV ($\sim 30\%$ change). The normalizations of both the outermost regions for the azimuthal average and the south-east changed within 5% and 15%, respectively. The shapes of the ICM spectra around 2–3 keV and the CXB one with the power-law index of 1.4 are different from each other in the energy band. The ICM temperature in the outermost region, therefore, does not suffer significantly from the CXB level and fluctuation. As a result, even if we consider such uncertainties, the resultant values of the electron temperature, density, and the entropy for the ICM components do not significantly change by the NXB, CXB, and OBF contaminant systematics.

We also estimated the fraction of photons entering from outside of the extracted regions using a simulator of the Suzaku XRT/XIS system “xissim” tool. When a much brighter region is outside of the extracted region, photon contamination from the bright source would affect significantly in such cluster outskirts observations. Moreover, the point spread function of the Suzaku XRT has an extended tail (see e.g., Sato et al. 2007). We, thus, need to estimate the fraction to confirm the results derived from the spectral fits. If we assumed a β -model of Abell 1246 emission, as described in section 3, extending beyond the virial radius, the scattering and stray light contamination of the outermost region from other regions including the bright core would be within $\sim 15\%$ in the spectral fits.

5. Results and Discussion

5.1. Temperature and Density Profiles

The ICM temperatures in the annular regions of the cluster clearly decrease towards the virial radius. The temperature in the region $7'56 < r < 10'8$ ($1.2\text{--}1.8 r_{500}$) drops to $\sim 35\%$ of the peak temperature as shown in figure 4. The radial axis in figure 4 is normalized by $r_{500} \sim 6'1$, which is derived from the mass estimation of our observations under the H.E. assumption as mentioned in subsection 5.2. This decrease is slightly larger than the previous Suzaku results of other clusters (Bautz et al. 2009; Reiprich et al. 2009; Hoshino et al. 2010; Sato et al. 2010; Akamatsu et al. 2011). The metal abundance is almost consistent at ~ 0.2 solar from the central to the outer region of the cluster, although the abundance in $r > 0.5 r_{500}$ has large errors. The abundance of the central region is much lower than the values of the other clusters. These temperature and abundance are consistent with ASCA previous results, 5.17 ± 0.58 keV and 0.26 ± 0.17 solar in the whole cluster region, respectively, in Fukazawa et al. (2004), but our results provides a better accuracy and radial distributions of the temperature and abundance.

In order to investigate the directional dependence of the temperature, we derived the temperatures from the spectra of the four directions in the radius range of $2'16 < r < 5'40$ ($0.4 < r < 0.9 r_{500}$) and $5'40 < r < 10'8$ ($0.9 < r < 1.8 r_{500}$) as shown in figure 1 right. In the fits, the values of the CXB and Galactic components were fixed to those of the default case in table 2. The south-east direction tends slightly to have a lower temperature than the other directions, although those difference are within the statistical and systematic errors. Note that the southeast direction has higher statistic because the region is covered by both the center and offset observations with Suzaku.

We calculated the electron density from the normalization of the ICM spectral fits by considering the projection effect. The apec normalization parameter is defined as $Norm = 10^{14} \int n_e n_H dV / [4\pi(1+z)^2 D_A^2] \text{ cm}^{-5}$, where D_A is the angular diameter distance to the source. We estimated the deprojected $n_e n_H$ values assuming spherical symmetry and a constant temperature in each annular region and then assumed $n_e = 1.2 n_H$. We fitted the density profile with the β -model over all regions. The derived β value of the deprojected electron density profile is $\beta = 0.47 \pm 0.02$, which agrees with the value in Fukazawa et al. (2004). The electron density of the annular regions to r_{500} is also consistent with the previous XMM-Newton results for several clusters in $z < 0.2$ (Croston et al. 2008). We also investigated the directional difference of the electron density profile. The deprojected electron densities of the northeast and southwest regions for $0.9 < r < 1.8 r_{500}$ tend to be lower than those of the southeast and northwest regions as shown in figure 4.

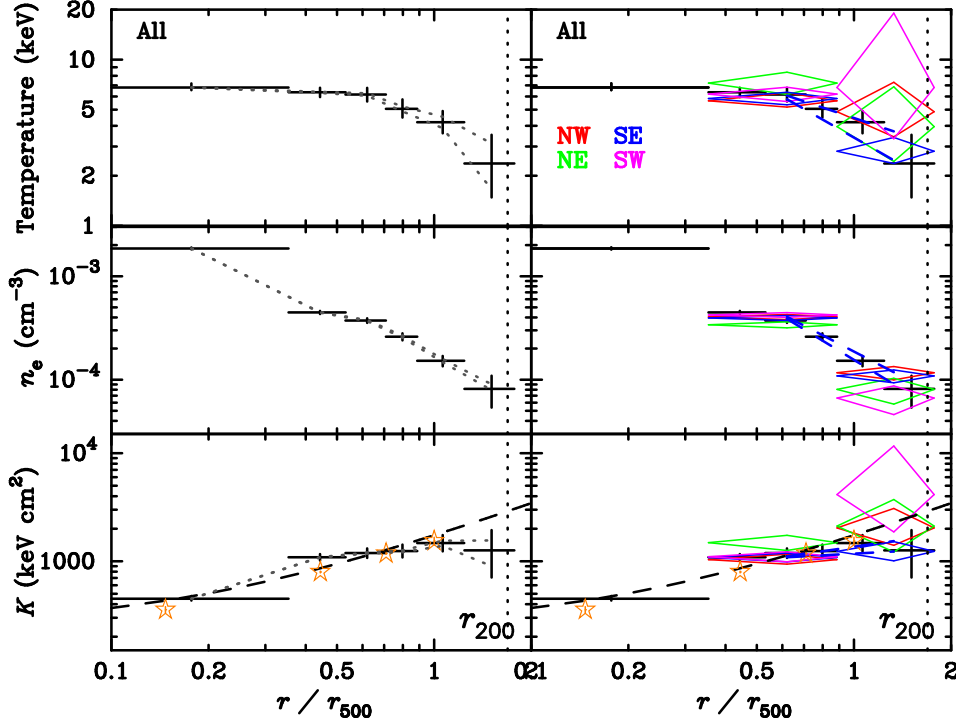


Fig. 4. Radial profiles of electron temperature (upper), density (middle), and entropy (lower) as a function of radius in units of r_{500} , where r_{500} is defined as 6'.1 derived from the mass profile. Black crosses show the values for the annular regions in each panel. Red, green, blue, and magenta diamonds in right panels correspond to the directional regions of northwest (NW), northeast (NE), southeast (SE), and southwest (SW) regions, respectively. The dashed lines in the lower panels indicate the best fit of the function $K \propto r^{1.1}$, as mentioned in subsection 5.3. Orange stars show the previous XMM-Newton results in Pratt et al. (2010). Here, the dotted lines in the left panels and blue dashed lines in the right panels are corresponding to the values by changing the CXB level by $\pm 10\%$, and $\pm 20\%$ which is a comparable to the estimated CXB fluctuation, respectively.

5.2. Mass Profile

We derived the gravitational mass of Abell 1246 assuming spherical symmetry and H.E. (hereafter H.E. mass). Under the assumption, the total integrated gravitational mass $M_{<R}$ within the three-dimensional radius R is given by

$$M_{<R} = -\frac{kTR}{\mu m_P G} \left(\frac{d \ln \rho_{\text{gas}}}{d \ln R} + \frac{d \ln T}{d \ln R} \right) \quad (1)$$

where G is the gravitational constant, μ is the mean molecular weight of the gas and m_P is the proton mass. We fitted the temperature and electron density profiles with the β -model formula separately as shown in figure 5, and then derived the H.E. mass with the fitted parameters. The gas mass density ρ_{gas} is expected to be given as $\rho_{\text{gas}} = 1.92 \mu m_P n_e$ with $\mu = 0.62$ and the ion density including helium is $n_i = 0.92 n_e$. We also calculated the overdensity to the critical density of the universe from the derived H.E. mass and found the $r_{500} = 6'.1$. On the other hand, the $r_{200} = 9'.0$ derived from the H.E. mass profile deviated by $\sim 9\%$ from those estimated r_{200} by the empirical formula with the mean temperature in Henry et al. (2009).

The radial mass profile of figure 5 is normalized by the radius of r_{500} to enable easy comparison with the previous

results. The errors of the total gas mass profiles are derived from the sum of 90% errors of the fitted parameters of the temperature and electron density with the β -model formulae. Note that the resultant H.E. mass starts flattening or decreasing beyond the r_{500} region. One plausible cause is the systematic effect from the too simple model formula, such as a simple β -model. However, the other formulae also result in the similar feature for other clusters. The observed steep temperature drop is causing such a mass distribution (see also Bonamente et al. 2013; Ichikawa et al. 2013). Consequently, this feature would indicate a flaw in the H.E. assumption in $r > r_{500}$. Even if we use the temperature profile including the uncertainties of the CXB level by 10%, the feature does not change as shown by the dash-dotted line in figure 5 left. As mentioned in subsection 5.3, the flatness or decrease of the entropy in $r > r_{500}$ would also indicate being out of H.E. in the outskirts region of the cluster. Again, we note that although the derived mass indicates the azimuthal averaged mass, it would be affected by the higher statistic of the southeast direction.

The derived H.E. mass within $r < r_{500}$ from our data is $(4.3 \pm 0.4) \times 10^{14} M_{\odot}$. It is consistent with that by Vikhlinin et al. (2009), $(3.9 \pm 0.1) \times 10^{14} M_{\odot}$ at r_{500} derived with the $M_{500}-T_X$ scaling relation with Chandra observations. It is useful to compare the cluster mass with

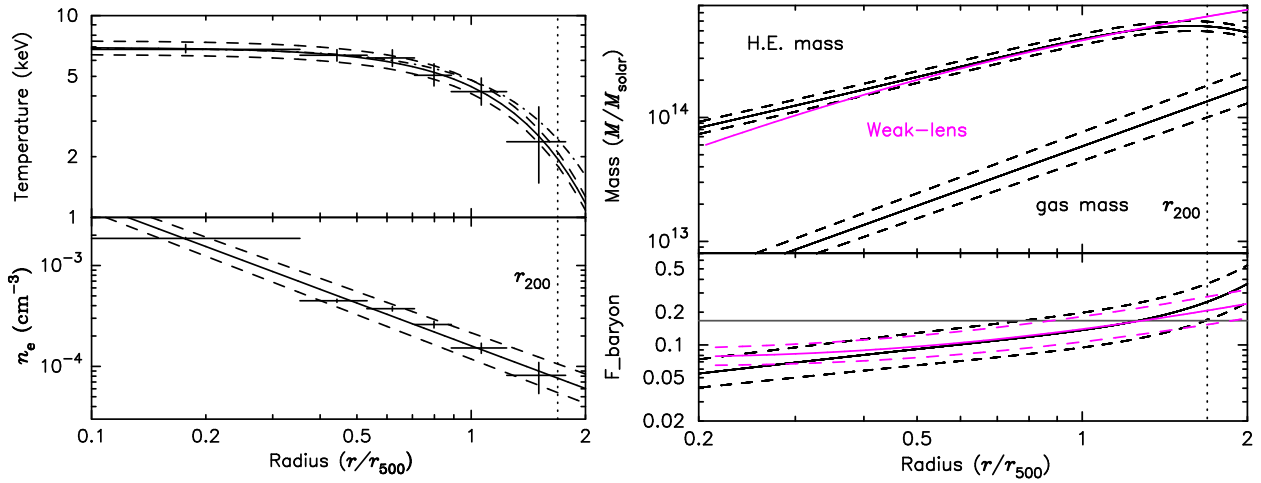


Fig. 5. (Left) The resultant fits of the temperature (upper) and electron density (lower) as a function of radius in units of r_{500} . Solid and dashed lines correspond to the best fit and $\pm 90\%$ errors, respectively. The dash-dotted line shows the upper limit of the fits considering the CXB fluctuation by 10%. (Right) Upper panel: The H.E. mass and gas mass (upper and lower black solid lines, respectively) of Abell 1246 cluster from our data. Each dashed line shows $\pm 90\%$ errors. The magenta line shows the gravitational mass profile from weak-lens observations for lower mass cluster sample (Okabe et al. 2010). Lower panel: Radial profile of the gas mass fraction to the H.E. mass (black) and the gravitational mass from weak-lens observations (magenta). Dashed lines show $\pm 90\%$ errors. The light gray line indicates the cosmic baryon fraction (Komatsu et al. 2011). The vertical dotted line corresponds to r_{200} with the mean temperature by the formula in Henry et al. (2009).

several methods to avoid systematic bias. We, therefore, compare the H.E. mass with the gravitational mass from weak-lens observation. Okabe et al. (2010) derived the gravitational mass profile based on the Navarro-Frenk-White (NFW) model (Navarro et al. 1996) for the lower and higher mass cluster sample with $\sim 10\%$ relative accuracies. When we compare the H.E. mass profile from our data with the mass profiles from the lower and higher mass sample, the former profile agrees well. Using the parameters for the lower mass sample, the calculated gravitational mass within r_{500} and r_{200} are 4.2 and $6.5 \times 10^{14} M_{\odot}$, respectively. As shown in figure 5, the H.E. mass and the mass from the lower mass sample are fairly consistent within r_{500} , and beyond this radius the mass from weak-lens is larger than that from our data.

The fraction of the derived gas mass to the H.E. mass from our data around r_{500} is $14^{+6}_{-5}\%$, which is consistent with the cosmic baryon fraction value of 16.7% (Komatsu et al. 2011) within the statistical error. As described above, because the $r > r_{500}$ region is apparently not in H.E., we calculated the fraction at r_{200} with the gravitational mass from weak-lens observation. The gas mass at r_{200} is derived to be $(1.4 \pm 0.4) \times 10^{14} M_{\odot}$ from our observation, and the gas mass fraction using the weak-lens template model is $(21 \pm 5)\%$, which also agrees with the cosmic baryon fraction. Because the typical scattering of the relation between the cluster mass and the concentration parameter of the NFW model for lower mass cluster sample in Okabe et al. (2010) is $\sim 10\%$, the fraction still agrees with the cosmic baryon fraction.

In the region around r_{500} , we compared the slope of the mass density of Abell 1246 with the expected slope $\rho \propto r^{-3}$

from the NFW profile. The mass density slope from our result seems to be steeper than the one derived from the NFW model. Kawaharada et al. (2010) and Akamatsu et al. (2011) also suggest such a steeper mass profile in the outer region of the clusters. This will be real but systematic error such as H.E. assumption validity shall be critically reviewed, which is beyond the scope of this paper. If the H.E. assumption was invalid in this region, we would have to estimate the cluster mass, particularly in the outskirts, with weak-lens observations.

5.3. Entropy Profile

An entropy profile provides the thermal process and history of the ICM, particularly for the gas heated by the accretion shock from outside of the cluster. In X-ray astronomy, we define the entropy as $K = kTn_e^{-2/3}$. The resultant entropy profile in the annular regions is shown in the lower panels of figure 4. The entropy increases with radius to $\sim r_{500}$, and the profile has a flatter slope at $r > r_{500}$. This tendency is consistent with previous Suzaku results (Bautz et al. 2009; George et al. 2009; Hoshino et al. 2010; Akamatsu et al. 2011). Compared to the previous XMM-Newton results of 31 clusters within r_{500} in Pratt et al. (2010), our results agree with the entropy profile within r_{500} as shown in figure 4. We also investigated the directional difference of the entropy in the same manner as the temperature and electron density profiles. Although the values in the outermost region have large errors, the entropy of the southeast direction tends to be lower than those of the other directions.

Voit (2005) reports $K \propto r^{1.1}$ on the basis of numerical simulations of adiabatic cool gas accretion, and the XMM-

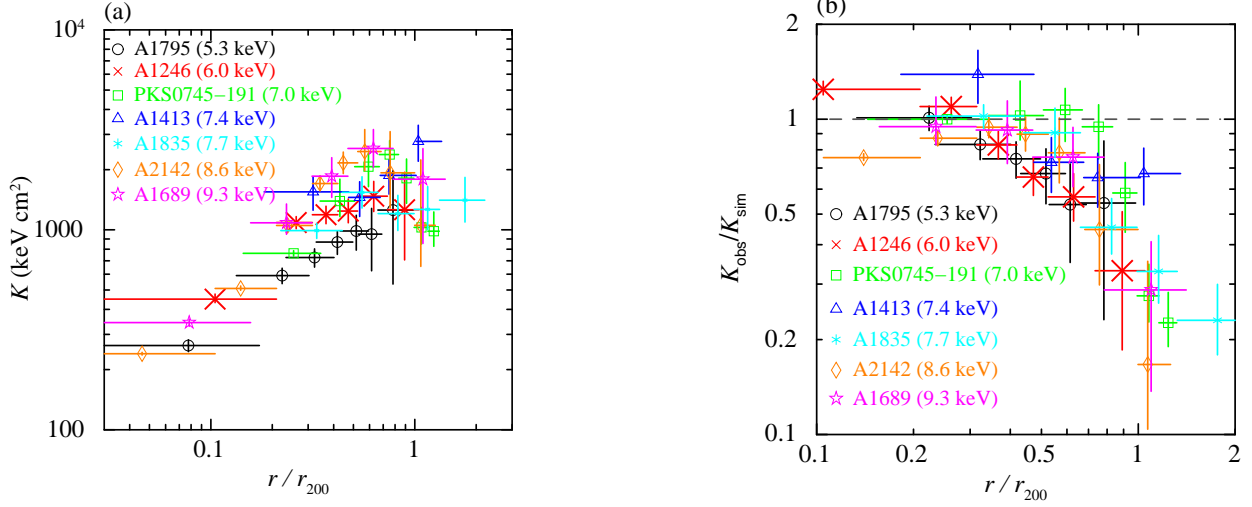


Fig. 6. (a) Derived radial entropy profile for each cluster from Suzaku observations. The radii are normalized by r_{200} with the mean temperature as shown in Henry et al. (2009). (b) Ratios of the entropy from X-ray observations to the expected values from the simulations. Dashed line shows the entropy from the simulations.

Newton results (Pratt et al. 2010) agree with the relation within r_{500} . We, therefore, fitted our entropy profile for the annulus regions by a power-law model with an index of 1.1. The best fit is shown by the dashed line in the lower panel of figure 4. Our result matches well with the model within r_{500} , while, in $r > r_{500}$, our result tends to have a smaller index. As for directional dependence, the entropy of the southeast direction shows a smaller index than the model, and the indexes of the other directions agree with the model, although they have large errors.

We compared our result with other results from Suzaku, Abell 1795 (Bautz et al. 2009), PKS0745-191 (George et al. 2009; Walker et al. 2012), Abell 1413 (Hoshino et al. 2010), Abell 1835 (Ichikawa et al. 2013), Abell 2142 (Akamatsu et al. 2011), Abell 1689 (Kawaharada et al. 2010), as shown in figure 6 (a). Here, the radius is normalized by r_{200} with the mean temperature as shown in figure 6, for each cluster, using the equation in Henry et al. (2009). All the clusters observed with Suzaku have a similar tendency that the entropy increases with radius until $r_{500} \sim 0.5 r_{200}$, and the profile has a flatter slope in $r > r_{500}$. In order to correct the subtle mass dependence of the profile, we examined ratios of the derived entropy from Suzaku observations to the expected values from the numerical simulation in Voit (2005), for all the clusters as shown in figure 6 (b). As a result, all the clusters regardless of the system size have a similar deviation tendency in $r > 0.5 r_{200}$.

Plausible causes of the flattening of the entropy profile, which are explained in previous Suzaku papers, are a flaw in the H.E. assumption, clumpiness, or both in the outer region of clusters. Kawaharada et al. (2010) suggest that the kinetic motions such as bulk or turbulence motions are required under the condition. As mentioned in Simionescu et al. (2011), the clumpiness which comes from the accreting gas from the filamentary structure in

the universe could overestimate the gas density (Nagai & Lau 2011) and increase the flattening of the entropy profile in the outer region of clusters. In Abell 1246 cluster, however, entropy flattening appears in the southeast region rather than the northwest region, which appears to be accreting from the filament. Another plausible cause is a difference between ion and electron temperatures in the outer low-density region of clusters, while the electron temperature is equal to the ion temperature in the central region of the clusters, because the equilibration timescale for electron-ion collisions is much longer than the elapsed time after the shock heating (Hoshino et al. 2010; Akamatsu et al. 2011).

In near future, X-ray microcalorimeter, such as the SXS instrument on ASTRO-H (Mitsuda et al. 2010), which has a 20–30 times higher energy resolution than CCD instruments, allows us to investigate the kinetic motions and the difference between the electron and ion temperatures. However, because of the small effective area of the SXS, these values are accessible only in the core region of the bright cluster such as the Perseus cluster. For the observations of the faint region such as the cluster outskirts, we would need to wait for the satellite with the larger effective area and field of view, such as DIOS (Ohashi et al. 2010). For resolving the clumpiness, the imaging analysis with the higher angular resolution would be needed, or the comparison of the density from the X-ray and Sunyaev-Zeldovich effect (e.g., Sunyaev & Zeldovich 1970; Sunyaev & Zeldovich 1972) observations could be also useful.

5.4. Upper Limit of Oxygen Emission Lines

The warm gas in the large-scale filament is an important part of the WHIM which is the dominant component of baryons in the local universe (e.g., Yoshikawa et al. 2003). Although Suzaku observations in several clusters of galaxies and superclusters have been performed to search for

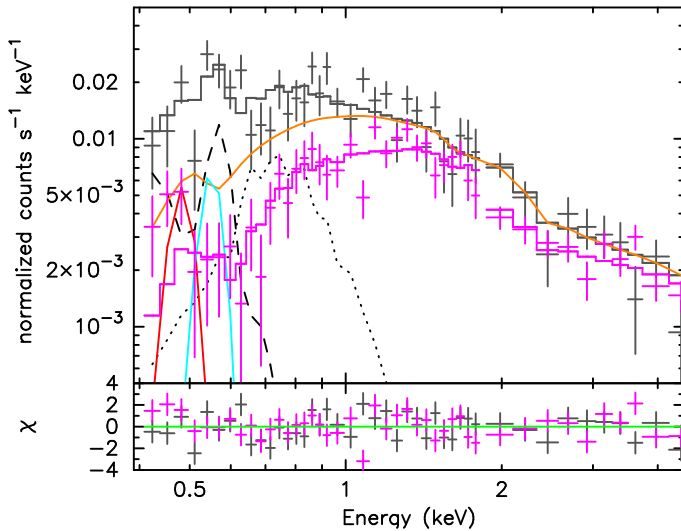


Fig. 7. Panel showing the resultant fits for the constraint of the intensities of the O VII and O VIII lines in the outside region of the virial radius. The O VII and O VIII emission lines are shown by red and light-blue lines, respectively, and the notations of the other lines are the same as in figure 3.

Table 4. Resultant intensities of O VII and O VIII emission lines with a 2σ confidence range.

O VII	
Center (keV) at $z = 0.1902$	0.482(fixed)
Sigma	0 (fixed)
$I (\times 10^{-7} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2})$	$1.3^{+1.6}_{-1.3}$
O VIII	
Center (keV) at $z = 0.1902$	0.549(fixed)
Sigma	0 (fixed)
$I (\times 10^{-7} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2})$	$2.1^{+3.5}_{-2.1}$

the redshifted O emission lines from the WHIM, no positive detection has been obtained. We fitted the spectra taken outside of the virial radius, $r > 10.8 \sim r_{200}$ of the cluster. This region is the same as the one used to estimate the fore- and background emissions, as shown in subsection 4.2. Although the spectra in this region were well represented by the Galactic and CXB components without an additional model as mentioned in subsection 4.2, we constrained the upper limit of the electron density of the thermal model of $\sim 1 \text{ keV}$ (model III), $7.5 \times 10^{-5} \text{ cm}^{-3}$ as the 2σ confidence limit, under the assumption that the ICM emission extended to the radius with a spherical symmetry. If the gas emission came from the filamentary structure, i.e. WHIM, in the line of sight depth of 20 Mpc, the n_H would be $8.5 \times 10^{-5} \text{ cm}^{-3} (L/20 \text{ Mpc})^{-1/2}$. Assuming that the gas temperature from the filamentary structure should be much lower, we investigated the upper limit of the intensities of the additional O VII and O VIII lines at the cluster redshift from the WHIM origin, be-

cause those emission lines would be more sensitive than the thermal component to constrain the WHIM signal in the lower temperature. We fitted the data with the following model: $\text{apec}_{\text{LHB}} + \text{phabs} \times (\text{apec}_{\text{MWH}} + \text{pow}_{\text{CXB}} + \text{gaussian}_{\text{OVII}} + \text{gaussian}_{\text{OVIII}})$. Here, the parameters of the Galactic and CXB components followed our previous fit values in the default case of table 2. The temperatures of the Galactic components and the photon index of the CXB component were fixed, and the normalizations were free in the fit. The redshifted central energies of the O VII and O VIII Gaussian lines were fixed at 482 and 549 eV, respectively, with no intrinsic width of the lines assumed. We employed an increment of $\delta\chi^2 = 4$ as the measure for the 2σ upper limits of the line intensities. This value also corresponds to the 95% limit for an additional single parameter (single line intensity) in the F-test. As a result, we determine the upper limit of the O VII and O VIII lines to be 2.9 and $5.6 \times 10^{-7} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$ as the 2σ confidence limits as shown in table 4 and figure 7. The resultant values are consistent with the results in Takei et al. (2007), Sato et al. (2010), and Mitsuishi et al. (2012) within 2σ error. Assuming 20 Mpc for the line-of-sight depth of the WHIM distribution, we constrain the density of the WHIM cloud under the condition of the temperature to be $T = 2 \times 10^6 \text{ K}$. Using the line intensity, $I < 2.9 \times 10^{-7} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2}$ at $z = 0.1902$, and the ratio of electron to hydrogen number density of $n_e/n_H = 1.2$ for ionized gas the following condition is obtained:

$$n_H < 4.7 \times 10^{-5} \text{ cm}^{-3} (Z/0.2 Z_\odot)^{-1/2} (L/20 \text{ Mpc})^{-1/2}$$

The corresponding overdensity $\delta \equiv n_H/\bar{n}_H$ is

$$\delta < 160 (Z/0.2 Z_\odot)^{-1/2} (L/20 \text{ Mpc})^{-1/2}. \quad (3)$$

Our upper limits for the O VII and O VIII lines are consistent with the previous Suzaku observations (Takei et al. 2007; Tamura et al. 2008). As for the WHIM search, a new mission which can separate the WHIM originated O VII and O VIII emission lines (e.g. the DIOS mission, Ohashi et al. 2010) will be needed.

5.5. Interpretation of the Morphology of Abell 1246

The X-ray image of Abell 1246 is obviously elongated to the northwest-southeast direction. This follows the galaxy density map, whose ratio of the major to minor axis of the density is about 2, as shown in figure 1. If the intracluster gas is under the condition of H.E. in the gravitational potential dominated by the dark matter, gas distribution should deviate from the spherical symmetry.

Comparing to Abell 1689 reported in Kawaharada et al. (2010), the temperatures for Abell 1246 and Abell 1689 in the direction which connects to an overdense filamentary structure of galaxies, are higher than those in the other direction. However, the temperatures in the other direction for Abell 1246 are relatively high unlike with those in Abell 1689. As shown in figure 1 right, the galaxy distribution around Abell 1246 is extended to the northwest-southeast direction. In fact, a comparison of the northwest and southeast regions reveals that the temperature

and entropy of the northwest region are higher than those of the southeast, while both electron densities are consistent. While the entropy of the southeast region has a flatter slope, the entropy of the northwest region agrees with slope from the numerical simulation.

If the gas infalls in an asymmetric manner from the filament onto the relaxed cluster and the accreted gas is not mixed with the original intracluster gas, the gas profile deviates from the spherical symmetry and the X-ray morphology becomes elliptical. In fact, Kawaharada et al. (2010) find a hot spot in the direction of the filament, and our results suggest the same condition. These facts would imply the same scenario of the accreting matter to the clusters.

6. Summary

We studied the electron temperature, density, cluster mass and entropy profiles in Abell 1246 cluster and around the cluster outskirts beyond the virial radius observed with Suzaku. We summarize the resultant features of Abell 1246 cluster as follows;

- The temperature drops from ~ 7 keV at the central region to ~ 2.5 keV around r_{200} region of the cluster.
- The calculated total mass within r_{500} under the H.E. assumption is $(4.3 \pm 0.4) \times 10^{14} M_{\odot}$ and the gas mass fraction agrees with the cosmic baryon fraction.
- The derived entropy profile has a flatter slope compared to the expected slope from the numerical simulation in $r > r_{500}$.
- In order to compare our results with other cluster results with Suzaku, we investigated the ratios of the observed entropy to the expected value from the numerical simulation. The resultant radial entropy ratios for each cluster have a similar tendency.
- We constrain the intensities of O VII and O VIII lines at the cluster redshift to be less than 2.9 and 5.6×10^{-7} photons $\text{cm}^{-2} \text{s}^{-1} \text{arcmin}^{-2}$, respectively, as 2σ upper limits. The intensity of O VII indicates $n_{\text{H}} < 4.7 \times 10^{-5} \text{cm}^{-3} (Z/0.2 Z_{\odot})^{-1/2} (L/20 \text{ Mpc})^{-1/2}$, which corresponds to the overdensity, $\delta < 160 (Z/0.2 Z_{\odot})^{-1/2} (L/20 \text{ Mpc})^{-1/2}$.

In the near future, X-ray microcalorimeter missions such as DIOS would give a lot of hints for investigating cluster outskirts. Also, we would have to estimate the cluster properties in several ways without bias effects.

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Appendix 1. Comparisons of the CXB intensity with the previous results

We estimate the CXB surface brightness in our observations to be $5.88_{-0.38}^{+0.41} \times 10^{-8} \text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ from the spectral fit after the point-like sources subtractions as

shown in table 2. The previous ASCA result (Kushino et al. 2002) shows the CXB surface brightness, $(6.38 \pm 0.07 \pm 1.05) \times 10^{-8} \text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$, (90% statistical and systematic errors) with the photon index, 1.412 in 2–10 keV. Moretti et al. (2009) also summarize the CXB level, including their new result with SWIFT. The derived CXB level in 2–10 keV from SWIFT is $(7.16 \pm 0.43) \times 10^{-8} \text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ with the photon index, $\Gamma = 1.47 \pm 0.07$. The measured CXB surface brightnesses show a significant range from the HEAO-1 value of $(5.41 \pm 0.56) \times 10^{-8} \text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ (Gruber et al. 1999) to $(7.71 \pm 0.33) \times 10^{-8} \text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ with SAX-MECS (Vecchi et al. 1999) in 2–10 keV. Because these measurements show the surface brightness to be within about 10% of the level reported by Kushino et al. (2002) with ASCA, we compare our estimation primary with those of Kushino et al. (2002), $I_0 = (6.38 \pm 0.07 \pm 1.05) \times 10^{-8} \text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. Here, we calculated the integrated point source flux per steradian from

$$I_{ps}(S > S_0) = \frac{k_0}{\gamma - 2} S_0^{-\gamma+2}, \quad (\text{A1})$$

where k_0 and γ are the differential $\log N$ – $\log S$ normalization and slope, respectively. We took nominal values, $k_0 = 1.58 \times 10^{-15} \text{sr}^{-1} (\text{erg cm}^{-2} \text{s}^{-1})^{\gamma-1}$ and $\gamma = 2.5$, from Kushino et al. (2002) as shown in Hoshino et al. (2010). S_0 was taken as $3 \times 10^{-14} \text{erg cm}^{-2} \text{s}^{-1}$, which corresponds to the faintest flux level of the point-like source in our analysis as mentioned in subsection 4.1. Note that the assumed $\log N$ – $\log S$ in equation (A1) does not take into account the flattening of the relation in the fainter flux end. The expected CXB surface brightness is $I_0 - I_{ps} = 4.56 \times 10^{-8} \text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$.

In addition, to estimate the amplitude of the CXB fluctuations, we also scaled the measured fluctuations from Ginga (Hayashida 1989) to our flux limit and the field of view (FOV) area. The fluctuation width is given by the following relation,

$$\frac{\sigma_{\text{Suzaku}}}{I_{\text{CXB}}} = \frac{\sigma_{\text{Ginga}}}{I_{\text{CXB}}} \left(\frac{\Omega_{\text{e,Suzaku}}}{\Omega_{\text{e,Ginga}}} \right)^{-0.5} \left(\frac{S_{\text{c,Suzaku}}}{S_{\text{c,Ginga}}} \right)^{0.25} \quad (\text{A2})$$

where $(\sigma_{\text{Suzaku}}/I_{\text{CXB}})$ means the fractional CXB fluctuation width due to the statistical fluctuation of discrete source number in the FOV. Here, we adopted $\sigma_{\text{Ginga}}/I_{\text{CXB}} = 5\%$, with S_{c} (Ginga: $6 \times 10^{-12} \text{erg cm}^{-2} \text{s}^{-1}$) representing the upper cut-off of the source flux, and Ω_{e} (Ginga: 1.2deg^2) representing the effective beam size (or effective solid angle) of the detector. The derived $\sigma_{\text{Suzaku}}/I_{\text{CXB}}$ was 4.9% with $\Omega_{\text{e,Suzaku}} = 0.09 \text{deg}^2$ for the Suzaku FOV, and $S_{\text{c,Suzaku}} = 3 \times 10^{-14} \text{erg cm}^{-2} \text{s}^{-1}$. As for the background region ($r > 10'8$) and the cluster outermost region ($7'56 < r < 10'8$) of the spectral fits for the azimuthal average, $\Omega_{\text{e}} = 0.04$ and 0.03deg^2 , we examined the fluctuation level to be 12.0% and 13.9% in the 90% confidence region, respectively. We also estimated the fluctuation from HEAO-1 A2 results (Shafer 1983) with $\sigma_{\text{HEAO-1}}/I_{\text{CXB}} = 2.8\%$, $\Omega_{\text{e,HEAO-1}} = 15.8 \text{deg}^2$, and $S_{\text{c,HEAO-1}} = 8 \times 10^{-11} \text{erg cm}^{-2} \text{s}^{-1}$. The derived $\sigma_{\text{Suzaku}}/I_{\text{CXB}}$ for the background region with the

HEAO-1 results was 17.3%. This value was slightly larger than that with ASCA. As for the directional dependence, because the CXB fluctuation of the eastern outer region, $5'40 < r < 10'8$ was 17.0% with $\Omega_{\text{e,Suzaku}} = 0.02 \text{ deg}^2$, we estimated the uncertainties from the fluctuation changing the CXB level by $\pm 20\%$ from the Ginga results. The resultant uncertainties are shown in figure 4.

As a result, the best-fit parameter of the CXB surface brightness for the background region, $r > 10'8$ (after subtraction of point sources brighter than $3 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ in 2–10 keV band) is $(5.88^{+0.41}_{-0.38} \pm 0.7) \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ which agrees with those of the previous Suzaku results (Hoshino et al. 2010; Ichikawa et al. 2013), although our resultant CXB surface brightness is slightly larger than the value expected one from the ASCA results ($4.56 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$) with the 90% statistical errors taking into account the CXB fluctuation. One plausible cause would be the contaminations from the excluded point-like source signals and unresolved sources.

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